Title:
Parametric CAD Framework for Design of Fish-Scale-Inspired Functional Surfaces

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Introduction:

Biomimetic surfaces have emerged as valuable approaches for reducing aerodynamic and hydrodynamic drag and biofouling and improving energy efficiency in applications such as shipping, aviation, ground transportation, and energy generation. Among biologically inspired structures, fish-scale-inspired surfaces have attracted considerable attention due to their multifunctionality, offering both protective and flexible characteristics in armor systems [3, 11] while also exhibiting anti-fouling behavior [5]. A key feature of fish scales is their potential to reduce hydrodynamic drag. Fish-scale-inspired surfaces have been produced using a wide range of microfabrication technologies [2, 8-11]. Experimental studies on loach-inspired geometries report drag-reduction (DR) rates between 9.42% and 17.25% for Reynolds numbers spanning 10,000 to 70,000, with peak reductions observed near a flow velocity of 1.5 m/s [10]. Goldfish-inspired surfaces have demonstrated a DR level exceeding 10% relative to a smooth surface at a test speed of 13.1 m/s [2], while European sea bass-inspired scale arrays exhibit net DR rates of approximately 27% [7]. Comparable drag reductions have also been reported for shark-skin-inspired riblet surfaces [4, 6]. Collectively, these studies indicate that biomimetic surface structures can enhance hydrodynamic performance; however, most investigations rely on fixed geometries that are neither readily designable nor easily adjustable, thereby limiting systematic design optimization to achieve optimal performance.

Although fish-scale-inspired microstructures have been demonstrated using isolated fabrication approaches, an integrated CAD workflow for automated geometric modeling of imbricated fish-scale surfaces and CAD-ready export to support downstream toolpath generation remains limited. This restricts scalable testing and systematic design optimization. Building on recent parametric CAD/CAM advances for micro V-groove structures [1], this study presents a parametric design framework composed of multiple functional blocks for the automated geometric modeling of periodic and overlapping (imbricated) fish-scale features populated over a flat surface. The framework establishes a direct link between biomimetic fish-scale geometry and CAD-compatible representations, extending beyond the triangular and related riblet geometries examined in prior studies [1, 4, 6], and providing a foundation for future CNC-based fabrication and performance validation.

Generalized CAD Framework for Design:

The development of functional surfaces involves a sequence of interconnected stages, beginning with geometric modeling and followed by fabrication and experimental evaluation of the manufactured prototypes. In line with this workflow, the proposed framework, illustrated in Fig. 1, comprises several functional blocks associated with the parameterization of the base workpiece, the geometry of individual fish-scale features, and the resulting functional structured surface. Each functional block (FB) represents a specific geometric definition or operation, with the link between blocks describing the information flow required to generate the framework's current output: a CAD solid model of the functional structured surface.

The CAD framework is organized into main function blocks (MFBs) that define the core modeling operations and secondary function blocks (SFBs) responsible for specifying the required design parameters. The main function blocks include the "Parametric Model" (MFB1) and the "CAD Solid Modeler" (MFB2). MFB1 provides an analytical, parameter-driven description of the functional structure using trigonometric relationships to define the geometry and its spatial distribution on the surface, while MFB2 converts this description into a corresponding CAD solid model suitable for visualization and, although not in this study, for numerical analysis and downstream applications.

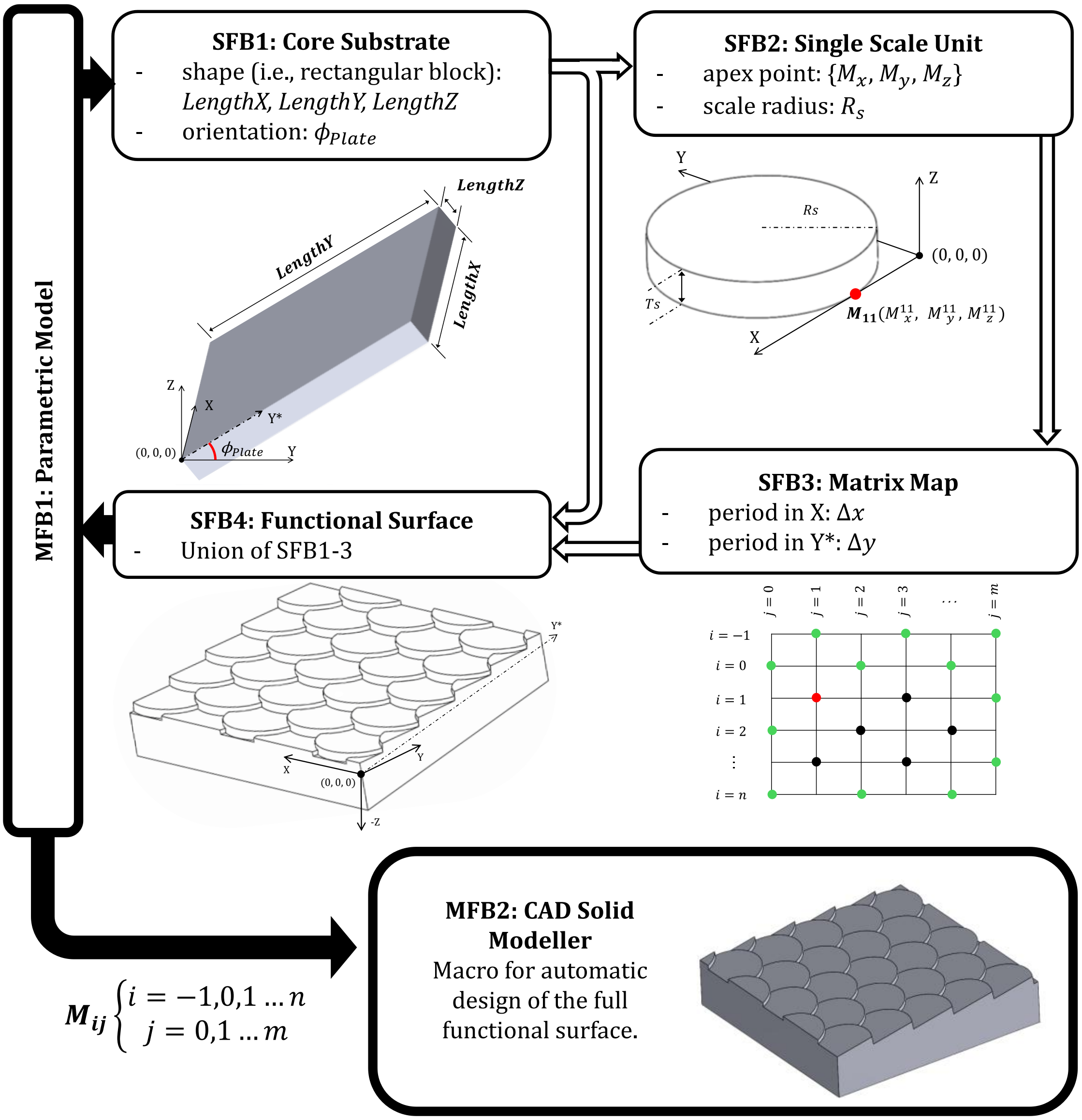

Fig. 1: CAD Framework.

Parametric Model of the Functional Structured Surface (MFB1):
The parametric model of the fish-scale functional surface is defined within MFB1 as a fully analytical representation of the surface geometry. The objective is to develop a complete geometric representation of the functional surface by combining a base substrate definition with a single repeatable geometric structure, which is replicated across the surface using a staggered matrix-based positioning scheme. To achieve this, MFB1 is decomposed into SFB1–4, where SFB1-3 each define a distinct, non-overlapping aspect of the overall geometry, while the combined output is assembled in SFB4 to generate the complete functional structured surface.

SFB1: Core Substrate and Reference Frame
SFB1 defines the base substrate geometry and establishes the global reference coordinate system used for all subsequent geometric constructions. The substrate is modeled as a rectangular plate characterized by the dimensions $LengthX$, $LengthY$, and $LengthZ$. A plate tilt angle, ϕ_{plate}, is applied to the substrate, resulting in a rotated reference direction denoted as Y^*, which lies within the YZ-plane. This tilted reference frame provides the geometric foundation for defining the orientation and placement of all surface structures.

SFB2: Single Scale Structure
A single fish-scale structure serves as the fundamental repeatable structure of the functional surface. Each scale structure is modeled as a cylindrical disk with radius R_S and thickness T_S, with its flat surfaces parallel to the XY-plane. The thickness is selected to satisfy an overlap/continuity constraint as a function of scale radius and plate tilt angle:

$$T_S = 2R_S \tan(\phi_{plate}) \tag{1}$$

To fully specify the spatial location of the scale structure, a frontal reference point is defined on the disk boundary (the point with maximum coordinate along the local forward direction), denoted as M_{ij}. Eqn. (2) describes the cylindrical structure defining a single structure. This formulation enables a consistent replication and positioning of the scale geometry across the substrate surface.

$$(x - M_x^{ij})^2 + (y + R_s - M_y^{ij})^2 = (R_s)^2,\; 0 \le z - M_z^{ij} \le T_S \tag{2}$$

SFB3: Matrix Map
The matrix map defines the spatial arrangement used to replicate individual scale structures across the substrate surface. All placement locations are specified on the top face of the base substrate within the XY^* plane. The discrete placement locations of scale structures are represented by their frontal point M_{ij}, where the indices i and j denote positions in the Y^*- and X-axes, respectively. Mathematically, the matrix indices define a staggered discretization, in which scale structures are placed only at alternating index locations using a parity rule (placements occur when $(i+j)$ is even) whereas the remaining index pairs are unused. In physical space, uniform periodic spacings Δx and Δy are imposed between adjacent scale structures along the two in-plane directions, as illustrated in Fig. 2. Additionally, phased rows are introduced such that successive rows are offset by $\Delta x / 2$ in the X-direction and $\Delta y / 2$ in the Y^*-direction, resulting in an effective half-period discretization along both axes. To account for geometric overlap at the substrate boundaries, the array dimensions are defined such that the required auxiliary placements are incorporated into the index ranges. In the Y^*-axis, the index extent is defined as:

$$n = \left\lceil \frac{2LengthY}{\Delta y} \right\rceil \tag{3}$$

Applying the ceiling function to the calculation ensures that the final auxiliary placement at the positive boundary is included. However, the geometry requires additional auxiliary placements below the substrate origin due to overlap effects. As a result, two auxiliary index layers preceding the active region are included because the feature footprint extends beyond its frontal point due to overlap, ensuring complete coverage at the negative boundary. This leads to the index range $i = -1, 0, 1, \ldots, n$. In the X-axis, a similar definition is used for m:

$$m = \left\lceil \frac{2LengthX}{\Delta x} \right\rceil \tag{4}$$

Consequently, the scale structures indexed by $j = 0, 1, \ldots, m$ are sufficient to cover the active substrate region and its associated boundary overlap.

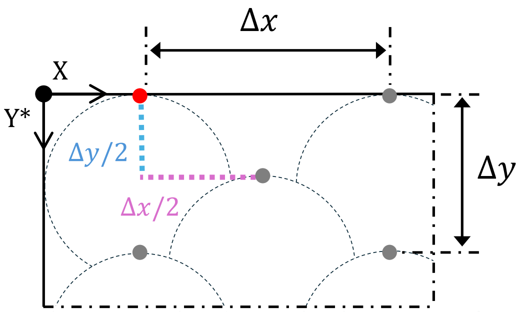

Fig. 2: Typical Physical Spacing of Frontal Scale Points

SFB4: Full Functional Structured Surface

The construction of the complete fish-scale functional surface is defined through the replication and spatial arrangement of the single scale structure defined in SFB2, using the matrix map specified in SFB3. Each scale structure is instantiated with a fixed orientation and referenced by its frontal point M_{ij}, which is positioned directly on the top surface of the core substrate in SFB1 within the XY^* plane. The functional surface is generated by replicating the scale structure at all matrix-defined frontal locations M_{ij}. While auxiliary placements are introduced to ensure full geometric coverage near the substrate boundaries, only the portions of the replicated volumes that lie within the physical limits of the substrate are retained. Specifically, the final functional structured surface is restricted to the domain $x \in [0, LengthX]$, $y^* \in [0, LengthY]$ with any geometry extending beyond these bounds removed. This trimming operation results in a rectangular boundary when the surface is viewed in the XY^* plane. In XY, the resulting geometry forms a two-dimensional pattern of overlapping scale structures. The three-dimensional structure of the functional surface arises from the relative vertical offset between successive rows of scales. The periodic spacing along the Z-axis (Δz) between overlapping rows is defined in Eqn. (5), that accounts for the inclined orientation of the substrate and produces the characteristic stepped topology of the fish-scale surface.

$$\Delta z = \Delta y \sin(\phi_{plate}) \tag{5}$$

Output of MFB1

The output of MFB1 is a complete analytical description of the fish-scale functional surface, expressed as a structured set of geometric structures defined by their frontal positions, shape parameters, and deterministic spatial relationships on the core substrate. This set can be represented as M_{ij}, where $i = -1, 0, 1, \ldots, n$ and $j = 0, 1, \ldots, m$, corresponding to the parametric indexing of the surface features. The resulting analytical representation serves as the direct input to MFB2, which is responsible for generating the corresponding CAD solid model of the functional surface.

Automated Generation of the Geometric Model (MFB2):
MFB2 is implemented through a CAD macro that operationalizes the analytical description produced by MFB1. Rather than defining new geometric relationships, this module interprets the indexed feature set M_{ij} and instantiates each fish-scale feature as a concrete geometric volume within the CAD environment, positioning it according to the prescribed spatial arrangement on the workpiece. The resulting feature volumes are combined to form the complete CAD solid model. An overview of the CAD macro structure is provided in Fig. 3.

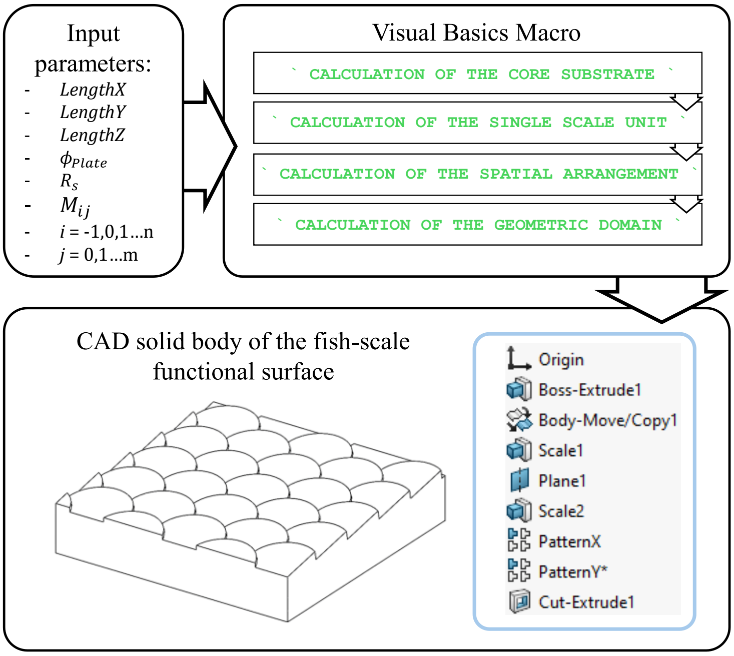

Fig. 3: Overview of the developed CAD macro.

Conclusions:
This study presents a CAD-based approach for the parametric design of fish-scale-inspired functional surfaces, structured through a modular decomposition of geometric definition and spatial distribution. By separating the base geometry, feature definition, and patterning operations into distinct functional blocks, the approach enables a systematic description of complex biomimetic surface geometries with controlled geometric interaction. A defined set of fish-scale geometric parameters is used to generate a corresponding CAD solid model of the functional surface.

The proposed approach provides a flexible CAD/CAM-oriented foundation for parametric design of fish-scale-inspired functional surfaces. The resulting geometric model provides a consistent basis for downstream fabrication and experimental evaluation. Future work will address CNC-based fabrication and functional performance testing of fabricated surfaces, with particular emphasis on drag-reduction performance. These efforts are intended to enable systematic assessment of fish-scale-inspired surface designs and to support the extension of fabrication strategies to complex micro- and nano-scale surface structures on both planar and free-form substrates, including cylindrical (drum-type) geometries.

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